

TITLE OF THE INVENTION

OFDM SIGNAL TRANSMISSION SCHEME, AND OFDM SIGNAL
TRANSMITTER/RECEIVER

5 BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates to an OFDM (Orthogonal
Frequency Division Multiplexing) transmission scheme, and more
specifically to a scheme for transmitting data via a wired or
10 wireless transmission path by using an OFDM signal, and a
transmitter/receiver therefor.

Description of the Background Art

In an OFDM signal transmission scheme, a demodulation
15 characteristic deteriorates due to any distortion observed in a
transmission path, out-of-synchronization after passage of time,
frequency drift between a transmission side and a reception side,
amplitude and phase errors resulted from phase noise in a local
oscillator provided in a receiver, and the like. Such error
20 factors provoking the demodulation characteristic to deteriorate
are hereinafter referred to as frequency response variation.

In the OFDM signal transmission scheme, for synchronization
with a receiver, a transmitter often inserts one or more preambles
into a signal before data transmission. The preamble is longer
25 than one symbol in time wise, and therewith, a frequency response

of the transmission path can be correctly estimated. The more preambles lead to the higher accuracy in estimating the frequency response, but the transmission speed shows a considerable drop.

Therefore, as is disclosed in Japanese Patent Laying-Open
5 No. 8-265293 (96-265293), interposing one or more pilot carriers in between data carriers in a data symbol is conventionally popular.

The OFDM signal is structured by a plurality of equal-length symbols, each of which includes several subcarriers. The
10 above-mentioned data carrier and pilot carrier are both subcarriers. In the above prior art, a phase error of the pilot carriers included in the data symbol is detected for every data symbol for compensation.

Such prior art, however, bears a problem in an environment
15 where any higher-level noise is observed in the transmission path or a multi-path fading environment. Therein, the fewer number of pilot carriers per symbol, the lower the accuracy of phase error detection becomes. Although the more number of pilot carriers surely achieve the higher accuracy thereof, the occupied
20 frequency bandwidth becomes wider, and the transmission speed considerably drops. Furthermore, it is difficult to compensate also the amplitude error caused by any distortion observed in the transmission path.

25 SUMMARY OF THE INVENTION

Therefore, an object of the present invention is to provide an OFDM signal transmission scheme and a transmitter/receiver therefor. With the OFDM signal transmission scheme, even in an environment where any higher-level noise is observed in the transmission path or a multipath fading environment, any frequency response variation of the transmission path, which is caused by any one or more of distortion observed in the transmission path, out-of-synchronization after passage of time, frequency drift between transmission and reception sides, and a residual phase error, is accurately compensated with respect to every subcarrier included in a symbol without dropping the transmission speed. Further, with such scheme, the OFDM signal is transmitted with a lower error rate.

The present invention has the following features to attain the object above.

A first aspect of the present invention is directed to a scheme for transmitting an OFDM signal from a transmission side to a reception side, wherein

the OFDM signal includes both a data symbol having data therein, and a pilot symbol having a frequency component predetermined in amplitude and phase,

on the transmission side, the pilot symbol is inserted before or after one or more the data symbols, and is transmitted together with one or more the data symbols, and

on the reception side, the received pilot symbol is utilized

for compensating a frequency response variation of a transmission path resulted from any one or more of distortion observed in the transmission path, out-of-synchronization with passage of time, frequency drift, and residual phase error.

5 As described above, in the first aspect, a pilot symbol having a predetermined frequency component predetermined in amplitude and phase is inserted between data symbols with a predetermined interval on the transmission side. On the reception side, a frequency response of a transmission path is
10 accurately estimated by using those pilot symbols. By utilizing the estimated frequency response and a difference in frequency response between any two pilot symbols away from each other for a predetermined number of data symbols, a frequency response variation of the data symbols between the pilot symbols is
15 compensated. In this manner, the data symbols can be correctly demodulated even in the multipath fading environment or high-level-noise environment.

 According to a second aspect, in the first aspect,
 every subcarrier included in the pilot symbol is a pilot
20 carrier predetermined in amplitude and phase.

 As described above, in the second aspect, the symbol length remains the same regardless of the number of subcarriers included therein. Accordingly, transmission speed does not drop even if one symbol wholly includes the subcarriers, and thus such OFDM
25 signal transmission scheme that the phase error is corrected with

higher accuracy can be implemented.

According to a third aspect, in the first aspect,
the pilot symbol is plurally and sequentially inserted
before or after one or more the data symbols.

5 As described above, in the third aspect, with the pilot
symbol inserted plurally in a row, the frequency response of the
transmission path can be estimated with higher accuracy on the
reception side. Therefore, the data symbols can be correctly
demodulated even in the multipath fading environment or high-
10 level-noise environment.

According to a fourth aspect, in the first aspect,
the pilot symbol is periodically inserted before or after
one or more the data symbols.

As described above, in the fourth aspect, with the pilot
15 symbol periodically inserted, the temporal location of the pilot
symbol can be easily detected when received.

According to a fifth aspect, in the first aspect,
the pilot symbol is non-periodically inserted before or
after one or more the data symbols.

20 As described above, in the fifth aspect, when the pilot
symbol is inserted non-periodically or with an irregular interval,
the insertion interval is determined depending on how speedy the
transmission path changes in state.

According to a sixth aspect, in the fifth aspect,
25 on the transmission side, the pilot symbol is adaptively

changed in frequency and number for insertion depending on a state of the transmission path.

As described above, in the sixth aspect, by adaptively changing the pilot symbol in frequency and number for insertion
5 depending on in what state the transmission path is, the transmission efficiency can be improved.

According to a seventh aspect, in the fifth aspect,
on the transmission side, the OFDM signal is provided with control information indicating how often the pilot symbol is
10 inserted and how many.

As described above, in the seventh aspect, by providing the transmission signal with the control information telling how often the pilot symbol is to be inserted in between the data symbols and how many, the pilot symbol and the data symbol are
15 discriminated from each other based on the control information at demodulation on the reception side.

According to an eighth aspect, in the first aspect,
the frequency response variation of the transmission path is compensated by using a compensation vector calculated, as a
20 time series linear approximation, from a difference in frequency response between any two pilot symbols closest to each other.

As described above, in the eighth aspect, the frequency response variation of the data symbols between the pilot symbols is compensated by linear approximation. In this manner, the phase
25 shift between the pilot symbols caused by the frequency drift

becomes linear with time. Therefore, compensation can be linearly done with accuracy. Further, with a proper interval of inserting the pilot symbols, the frequency response of the transmission path also becomes linear, allowing compensation
5 correctly and linearly done.

According to a ninth aspect, in the first aspect,
the frequency response variation of the transmission path resulted from either one or both of the frequency drift and the residual phase error is compensated by using a value calculated,
10 as a time series linear approximation, from a difference in phase between any two pilot symbols closest to each other.

As described above, in the ninth aspect, the phase error of the data symbols between the pilot symbols is compensated by linear approximation. In this manner, the phase shift caused by
15 the frequency drift becomes linear with time, and thus compensation can be linearly done with accuracy.

According to a tenth aspect, in the first aspect,
the frequency response variation of the transmission path is compensated by using an average value taken for a phase error
20 among pilot carriers in the pilot symbol.

As described above, in the tenth aspect, by averaging the phase error of the received pilot carriers, such OFDM signal transmission scheme that the phase error is corrected with higher accuracy can be implemented.

25 According to an eleventh aspect, in the tenth aspect,

the average value is calculated by weighing each amplitude value for the pilot carriers.

As described above, in the eleventh aspect, by calculating an average value after weighing each carrier in the received pilot symbol according to its amplitude, such OFDM transmission scheme
5 that the phase error can be corrected with higher accuracy can be implemented even if the received signal distorts in the transmission path and by noise.

A twelfth aspect of the present invention is directed to
10 an OFDM signal transmitter for transmitting an OFDM signal towards a reception side, comprising:

a data symbol generator for generating an OFDM data symbol after inputting data for transmission;

a pilot symbol generator for generating an OFDM pilot
15 symbol; and

a symbol selector for switching between signals provided by the data symbol generator and the pilot symbol generator so that the pilot symbol is inserted before or after one or more the data symbols.

20 As described above, in the twelfth aspect, a transmitter inserts a pilot symbol having a predetermined frequency component predetermined in amplitude and phase between data symbols with a predetermined interval. On the reception side, a frequency response variation of the data symbols is accurately estimated
25 by using those pilot symbols. In this manner, the data symbols

can be correctly demodulated even in the multipath fading environment or high-level-noise environment.

According to a thirteenth aspect, in the twelfth aspect, the data symbol generator comprises;

5 a frequency-domain data symbol generator for generating a frequency-domain data symbol after inputting data for transmission; and

 an inverse Fourier transformer for subjecting a signal provided by the frequency-domain data symbol generator to
10 inverse Fourier transform, and

the pilot symbol generator comprises:

 a frequency-domain pilot symbol generator for generating a frequency-domain pilot symbol; and

 an inverse Fourier transformer for subjecting a
15 signal provided by the frequency-domain pilot symbol generator to inverse Fourier transform.

As described above, in the thirteenth aspect, the transmitter generates a signal having a predetermined frequency component predetermined in amplitude and phase and data symbols
20 as a frequency-domain signal, and then subjects the signal to inverse Fourier transform. In this manner, it becomes possible to generate an OFDM signal in a simplified structure, and accordingly, the data symbols can be transmitted with such simplified structure even in the multipath fading environment or
25 the high-level-noise environment.

A fourteenth aspect of the present invention is directed to an OFDM signal receiver for receiving, from a transmission side, an OFDM signal including a data symbol having data therein, and a pilot symbol having a frequency component predetermined in amplitude and phase and being inserted before or after one or more the data symbols, the receiver comprising:

a Fourier transformer for subjecting the received OFDM signal to Fourier transform;

a transmission path frequency response compensator for detecting the pilot symbol from a signal provided by the Fourier transformer, and with respect to the signal, compensating a frequency response variation of a transmission path; and

a demodulator for receiving the signal compensated with the frequency response variation of the transmission path, and demodulating the signal to output as demodulated data.

As described above, in the fourteenth aspect, on the transmission side, a pilot symbol having a predetermined frequency component predetermined in amplitude and phase is inserted between data symbols with a predetermined interval. On the reception side, a frequency response variation is accurately estimated by using those pilot symbols. In this manner, the data symbols can be correctly demodulated even in the multipath fading environment or high-level-noise environment.

According to a fifteenth aspect, in the fourteenth aspect, the transmission path frequency response compensator

calculates a compensation vector for compensation, by referring to a frequency response of a pilot symbol, a frequency response of another pilot symbol closest thereto, and a frequency response of a reference pilot symbol provided on a reception side, so that
5 a frequency response of the received data symbol corresponds to that of the reference pilot symbol.

As described above, in the fifteenth aspect, on the transmission side, a pilot symbol having a predetermined frequency component predetermined in amplitude and phase is
10 inserted between data symbols with a predetermined interval. On the reception side, a frequency response variation of the transmission path is accurately estimated by using those pilot symbols. The estimated frequency response is compared with a difference in frequency response between any two pilot symbols
15 away from each other for a predetermined number of data symbols. By referring to the difference, a frequency response variation of the data symbols interposed between the pilot symbols is compensated, allowing the data symbols to be demodulated correctly even in the multipath fading environment or the
20 high-level-noise environment,

According to a sixteenth aspect, in the fifteenth aspect, the compensation vector is calculated for every subcarrier included in the received data symbol by using every pilot carrier included in each of the pilot symbols.

25 As described above, in the sixteenth aspect, the

compensation vector is calculated for each of the subcarriers. Therefore, even if the receiver is used for a case where distortion level of the transmission path varies or out-of-synchronization is observed with time, for example, in mobile communications, the frequency response variation is compensated and the data symbols can be correctly demodulated.

According to a seventeenth aspect, in the fifteenth aspect, the compensation vector is calculated as a time series linear approximation from the frequency response variation between any two pilot symbols closest to each other.

As described above, in the seventeenth aspect, the frequency response variation of the data symbols between the pilot symbols is compensated by linear approximation. In this manner, when the transmission path seems to linearly change in state between the pilot symbols, compensation can be linearly and correctly done. Further, the phase shift caused by the frequency drift is linear with time, allowing linear compensation with accuracy.

According to an eighteenth aspect, in the fourteenth aspect,

the transmission path frequency response compensator comprises:

a pilot symbol detector for detecting both a first pilot symbol being an arbitrary pilot symbol and a second pilot symbol transmitted after the first pilot symbol;

a first pilot symbol transmission path frequency response calculator for calculating a first pilot symbol transmission path frequency response by dividing a frequency response of the first pilot symbol by that of a reference pilot symbol provided on a reception side;

a second pilot symbol transmission path frequency response calculator for calculating a second pilot symbol transmission path frequency response by dividing a frequency response of the second pilot symbol by that of the reference pilot symbol;

10 a compensation vector calculator for calculating, after inputting the first and second pilot symbol transmission path frequency responses, a compensation vector for compensating the frequency response variation of the transmission path; and

a frequency response compensator for compensating the frequency response of one or more the data symbols after inputting the compensation vector.

As described above, in the eighteenth aspect, on the transmission side, a pilot symbol having a predetermined frequency component predetermined in amplitude and phase is inserted between data symbols with a predetermined interval. On the reception side, the first and second pilot symbol transmission path frequency response are each calculated by dividing the first and second pilot symbols detected from the received signal by a predetermined reference pilot symbol, respectively. A difference therebetween is then obtained. By using the

difference, the compensation vector for the data symbols is each
calculated. Therefore, in this manner, any distortion observed
in the transmission path, out-of-synchronization after passage
of time, frequency drift, and residual phase error for the data
5 symbols can be correctly compensated.

A nineteenth aspect of the present invention is directed
to an OFDM signal receiver for receiving, from a transmission side,
an OFDM signal including a data symbol having data therein, and
a pilot symbol having a frequency component predetermined in
10 amplitude and phase and being inserted before or after one or more
the data symbols, the receiver comprising:

a Fourier transformer for subjecting the received OFDM
signal to Fourier transform;

a phase compensator for detecting the pilot symbol from a
15 signal provided by the Fourier transformer, and compensating the
signal for either one or both of frequency drift and residual phase
error; and

a demodulator for receiving the signal compensated with
either or both of the frequency drift and the residual phase error,
20 and demodulating the signal output demodulated data.

As described above, in the nineteenth aspect, on the
transmission side, a pilot symbol having a predetermined
frequency component predetermined in amplitude and phase is
inserted between data symbols with a predetermined interval. On
25 the reception side, a frequency response variation of the data

symbols is accurately estimated by using those pilot symbols. In this manner, the data symbols can be correctly demodulated even in the multipath fading environment or high-level-noise environment.

5 According to a twentieth aspect, in the nineteenth aspect, the phase compensator calculates a compensation value for compensation, by referring to a first difference between a phase of a pilot symbol and a predetermined phase, and a second difference in phase between any two pilot symbols closest to each other, so that a phase of the received data symbol corresponds to the predetermined phase.

10 As described above, in the twentieth aspect, a pilot symbol having a predetermined frequency component predetermined in amplitude and phase is inserted between data symbols with a predetermined interval on the transmission side. On the reception side, a frequency response of a transmission path is accurately estimated by using those pilot symbols. By utilizing the estimated frequency response and a difference in frequency response between any two pilot symbols away from each other for a predetermined number of data symbols, a frequency response variation of the data symbols between the pilot symbols is compensated. In this manner, the data symbols can be correctly demodulated even in the multipath fading environment or high-level-noise environment.

25 According to a twenty-first aspect, in the twentieth

aspect,

the first and second differences are each calculated by using a phase average value calculated for every pilot carrier included in each of the pilot symbols.

5 As described above, in the twenty-first aspect, such OFDM transmission scheme that the phase error can be corrected with higher accuracy can be implemented by averaging the phase of the received pilot carriers.

10 According to a twenty-second aspect, in the twenty-first aspect,

the phase average value is calculated by weighing each amplitude value for the pilot carriers.

As described above, in the twenty-second aspect, by calculating an average value after weighing each carrier in the received pilot symbol according to its amplitude, such OFDM
15 transmission scheme that the average value can be calculated with higher accuracy can be implemented even if the received signal distorts in the transmission path and by noise.

20 According to a twenty-third aspect, in the twentieth aspect,

the phase compensation value is calculated as a time series linear approximation from a difference in phase between any two pilot symbols closest to each other.

As described above, in the twenty-third aspect, the phase
25 error of the data symbols between the pilot symbols is compensated

by linear approximation. In this manner, the phase shift caused by the frequency drift becomes linear with time, and thus compensation can be linearly done with accuracy.

According to a twenty-fourth aspect, in the nineteenth
5 aspect,

the phase compensator comprises:

a pilot symbol detector for detecting both a first pilot symbol being an arbitrary pilot symbol and a second pilot symbol transmitted after the first pilot symbol;

10 a first pilot symbol phase difference calculator for calculating a difference between a phase of the first pilot symbol and a predetermined phase;

a pilot symbol phase difference calculator for calculating a difference in phase between the first pilot symbol and the second
15 pilot symbol;

a phase compensation value calculator for calculating, after inputting the phase difference value calculated by the first pilot symbol phase difference calculator and the phase difference calculated by the pilot symbol phase difference calculator, a
20 phase compensation value for compensating for the frequency drift and the residual phase error; and

a phase rotator for rotating, in response to the phase compensation value, the phase of the one or more data symbols.

As described above, in the twenty-fourth aspect, on the
25 transmission side, a pilot symbol having a predetermined

frequency component predetermined in amplitude and phase is inserted between data symbols with a predetermined interval. On the reception side, a difference in phase between the first pilot symbol to be first detected from the received signal and a reference pilot symbol provided on the reception side is found. Then, a difference in phase between the first and second pilot symbols. By utilizing the difference in phase, a phase compensation value for the data symbols can be obtained, allowing the frequency drift and residual phase error of the data symbols to be correctly compensated.

These and other objects, features, aspects and advantages of the present invention will become more apparent from the following detailed description of the present invention when taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. 1a to 1d are diagrams each showing the structure of an OFDM signal in a transmission scheme according to a first embodiment of the present invention;

FIG. 2 is a block diagram showing the structure of a transmitter of the first embodiment;

FIG. 3a and 3b are block diagrams each showing the structure of a DS_{ofdm} generator and a PS_{ofdm} generator in the transmitter of the first embodiment;

FIG. 4 is a block diagram showing the structure of a receiver

of the first embodiment;

FIG. 5 is a block diagram showing the structure of a TPFR compensator 6 in the receiver of the first embodiment;

FIGS. 6a and 6b are schematic views each for explaining subcarriers of a first pilot symbol and those of a reference symbol;

FIGS. 7a and 7b are schematic views each for explaining subcarriers of a second pilot symbol and those of the reference symbol;

FIG. 8 is a graph showing that a compensation vector can be calculated, through linear approximation, from a difference between first and second transmission path frequency responses;

FIG. 9 is a schematic view for explaining how a frequency response variation of subcarriers in a data symbol is compensated;

FIG. 10 is a block diagram showing the structure of a receiver according to a second embodiment of the present invention;

FIG. 11 is a block diagram showing the structure of a phase compensator 26 in the receiver of the second embodiment;

FIGS. 12a and 12b are schematic views each for explaining the subcarriers in the first pilot symbol and those in the reference symbol;

FIGS. 13a and 13b are schematic views each for explaining the subcarriers in the second pilot symbol and those in the reference symbol;

FIG. 14 is a diagram showing that a phase compensating value can be calculated, through linear approximation, from a phase difference between pilot symbols; and

FIG. 15 is a schematic view for explaining how phase compensation is carried out with respect to the subcarriers in the data symbol.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

(First Embodiment)

10 First, described below is a transmission scheme according to a first embodiment of the present invention. FIGS. 1a to 1d are diagrams each showing the structure of an OFDM signal to be transmitted under the transmission scheme of the first embodiment. As shown in FIGS. 1, a pilot symbol is accompanied by a plurality
15 of data symbols. The pilot symbol has a frequency component predetermined in amplitude and phase. After the data symbols, another pilot symbol follows. As such, the OFDM signal under the transmission scheme of the first embodiment takes such structure that the pilot symbol is inserted before and after one or more
20 data symbols. Herein, the number of pilot symbols to be inserted is not limited, but in a row if plurally provided.

The OFDM signal includes subcarriers, and the symbol length remains the same regardless of the number of subcarriers included therein. Accordingly, the subcarriers may be predetermined in
25 amplitude and phase wholly or partially. In order to compensate

the frequency response variation with higher accuracy, every subcarrier is preferably predetermined in amplitude and phase.

As already described above, under the OFDM signal transmission scheme, a signal to be transmitted is often provided with a preamble(s) in a transmitter for synchronization with a receiver. Such preamble is longer than one symbol in time wise, and may be inserted before or during transmission with an adaptively determined interval. Although the more preambles surely lead to the higher accuracy in compensating the frequency response variation, the transmission speed shows a considerable drop. Therefore, according to the transmission scheme of the first embodiment, the signal is preferably provided with the preamble before transmission or less often during transmission.

Further, the preamble may include control information telling how often the pilot symbol is to be inserted in between the data symbols and how many. If so, the control information is analyzed on the reception side so that the pilot symbol and the data symbol are discriminated from each other.

Still further, the control information may be inserted after an initial pilot symbol as a data symbol or a signaling symbol for transmitting information such as cue. If so, the control information as the OFDM signal can be correctly demodulated.

As such, the OFDM signal having pilot symbols inserted before and after one or more data symbols is transmitted from the transmission side. Those pilot symbols are utilized, on the

reception side, to estimate the frequency response of the transmission path with accuracy.

The estimated frequency response of the transmission path is compared with a frequency response of the transmission path
5 between any two pilot symbols away from each other for a predetermined number of data symbols for a difference therebetween. By referring to the difference, a frequency response variation of the data symbol(s) interposed between the pilot symbols is compensated. With such transmission scheme,
10 even in the multipath fading environment or the high-level-noise environment, the data symbols can be correctly demodulated.

Herein, as shown in FIG. 1a, the pilot symbol before the data symbol(s) is referred to as a first pilot symbol, and the one after as a second pilot symbol. The temporal interval
15 therebetween is taken longer if the transmission path does not change in state that much, but otherwise taken shorter as much to make the change linearly between the pilot symbols. As such, by adaptively changing the interval of inserting the pilot symbol depending on in what state the transmission path is, the
20 transmission efficiency is improved.

Note herein that the state of the transmission path may be measured and estimated on the transmission side, or measured on the reception side and then is fed back to the transmission side for determination.

25 The interval of inserting the pilot symbol may be periodic

or non-periodic. When the pilot symbol is periodically inserted, the temporal location thereof can be easily detected when received. In the case that the pilot symbol is inserted non-periodically or with an irregular interval, the insertion interval is
5 determined depending on how speedy the transmission path changes in state. Herein, the expression of the pilot signal being inserted non-periodically or with an irregular interval indicates that the pilot signal is not periodically inserted for the entire duration of signal transmission. Thus, the expression does not
10 exclude a case where the pilot symbol is periodically inserted for a short duration of signal transmission.

As a case for non-periodic insertion, as shown in FIG. 1b, the first pilot symbol is accompanied by a signaling symbol including the control information telling how often the pilot
15 symbol is inserted and how many. With such arrangement, the control information can be demodulated based on the frequency response of the transmission path estimated by using the first pilot symbol. In this manner, the demodulation is carried out more accurately than a case where the control information is
20 included in the preamble.

Note herein that, as shown in FIG. 1c, the first pilot symbol may be doubly provided so as to improve the accuracy in estimating the frequency response of the transmission path by the pilot
symbols. Further, as shown in FIG. 1d, the number of pilot symbols
25 for one insertion may be two or plural in a row. In such case,

for correct estimation, the frequency response of the transmission path is averaged for the pilot symbols.

The OFDM signal having such structure can be generated by a transmitter as described next below. FIG. 2 is a schematic view
5 structurally showing such transmitter according to the first embodiment of the present invention. Hereinafter, presumably, the number of data symbols is M , and the number of subcarriers per symbol is N .

In FIG. 2, the transmitter includes a DS_{ofdm} generator 1 for
10 generating a data symbol from transmitted data, a PS_{ofdm} generator 2 for generating a pilot symbol having such frequency component as described above predetermined in amplitude and phase, a symbol selector 3 for receiving two signals each from the DS_{ofdm} generator 1 and the PS_{ofdm} generator 2, and selecting either one of the signals
15 for output, and a D/A converter 4 for subjecting data provided by the symbol selector 3 to D/A conversion, and outputting a transmission signal. Herein, as to the DS_{ofdm} generator 1 and PS_{ofdm} generator 2, "DS" denotes "Data Symbol", and "PS" "Pilot Symbol". Further, "ofdm" accompanying DS and PS denotes that the symbol
20 is an OFDM signal.

Depicted in FIGS. 3a and 3b are block diagrams respectively showing the detailed structure of the DS_{ofdm} generator 1 and the PS_{ofdm} generator 2 in the transmitter of the first embodiment. In FIG. 3a, the DS_{ofdm} generator 1 includes a DS_f generator 11 and an
25 inverse Fourier transformer 12. Herein, as to the DS_f generator

11, "DS" denotes "Data Symbol", and "f" accompanying DS denotes that the symbol is a frequency-domain signal. In FIG. 3b, the PS_{ofdm} generator 2 includes a PS_f generator 21 and an inverse Fourier transformer 22. Herein, the above description for "PS" and "f" is also applicable to the PS_f generator 21.

Referring back to FIG. 2, data for transmission is provided to the DS_{ofdm} generator 1. The data is then converted into a data symbol, and is outputted to the symbol selector 3.

More specifically, referring to FIG. 3a, the data for transmission is first provided to the DS_f generator 11. The DS_f generator 11 outputs a frequency-domain data symbol, which includes many data carriers arranged on a frequency axis with a predetermined interval. This frequency-domain data symbol is subjected to inverse Fourier transform by the inverse Fourier transformer 12, and then is converted into a time-domain OFDM data symbol. After the conversion, the OFDM data symbol is provided to the symbol selector 3.

The above-described pilot symbol having the frequency component predetermined in amplitude and phase is generated in the PS_{ofdm} generator 2, and is outputted to the symbol selector 3.

In detail, referring to FIG. 3b, the PS_f generator 21 outputs the frequency-domain pilot symbol including many pilot carriers arranged on the frequency axis with a predetermined interval. The frequency-domain pilot symbol is subjected to inverse Fourier

transform by the inverse Fourier transformer 22, and is converted into a time-domain OFDM pilot symbol. After the conversion, the OFDM pilot symbol is provided to the symbol selector 3.

5 The symbol selector 3 selects either one of those two signals for output. Herein, the symbol selector 3 is assumed to output such signal as shown in FIG. 1a, in which pilot symbol insertion is made for every three data symbols.

10 If this is the case, the symbol selector 3 first selects the PS_{ofdm} generator 2 for its signal. After the pilot symbol is outputted, the symbol selector 3 then selects the DS_{ofdm} generator 1 for its signal. When three data symbols are outputted, the symbol selector 2 selects the PS_{ofdm} generator 2 for its signal. Thereafter, in the same manner, the symbol selector 3 selects the DS_{ofdm} generator 1 for its signal when another pilot symbol is
15 outputted. As such, by switching signals among two, the symbol selector 3 becomes capable of successively outputting such OFDM signal as shown in FIG. 1a.

Such signal outputted from the symbol selector 3 is provided to the D/A converter 4. The D/A converter 4 subjects the signal
20 to D/A conversion, and outputs the D/A converted signal as a transmission signal.

As is known from the above, the transmitter of the first embodiment inserts a pilot symbol having a frequency component predetermined in amplitude and phase in between data symbols with
25 a predetermined interval. With such transmitter, as long as the

frequency response variation of the data symbols is accurately compensated on the reception side by using those pilot symbols, data symbol transmission can be correctly done even in the multipath fading environment or the high-level-noise environment.

Depicted in FIG. 4 is a schematic view structurally showing a receiver according to the first embodiment of the present invention. In FIG. 4, the receiver includes a Fourier transformer 5 for subjecting a received signal to Fourier transform, a TPFR compensator 6 for compensating a frequency response variation of a signal provided by the Fourier transformer 5, and a demodulator 7 for demodulating a signal provided by the TPFR compensator 6. Herein, as to the TPFR compensator 6, "TPFR" denotes a transmission path frequency response.

The Fourier transformer 5 subjects every symbol to Fourier transform, and then outputs frequency-domain data. The outputted data is eliminated with the frequency response variation of the transmission path in the TPFR compensator 6. Thereafter, the data freed from the frequency response variation is demodulated as the data symbol in the demodulator 7.

FIG. 5 is a schematic view showing the structure of the TPFR compensator 6 in the receiver of the first embodiment. In FIG. 5, the TPFR compensator 6 includes a PS detector 61 for detecting the pilot symbol from the signal provided by the Fourier transformer 5; a PS1 TPFR calculator 62 for dividing the first

pilot symbol provided by the PS detector 61 by a reference pilot symbol; a PS2 TPFR calculator 63 for dividing the second pilot symbol provided by the PS detector 61 by the reference pilot symbol; a compensation vector calculator 64 for calculating a
5 compensation vector after receiving outputs from the PS1 and PS2 TPFR calculators 62 and 63; and a frequency response compensator 65 for compensating a frequency response of a signal provided by the PS detector 61 on the basis of an output from the compensation vector calculator 64. Herein, for the above components, "PS1"
10 denotes "first pilot symbol", and "PS2" "second pilot symbol".

The PS detector 61 detects the pilot symbol from the Fourier-transformed frequency-domain data. The PS1 TPFR calculator 62 divides the subcarriers in the first pilot symbol by those in the reference pilot symbol stored in memory (not shown)
15 in the receiver, thereby estimating the frequency response of the transmission path.

The reference pilot symbol stored in the memory is considered ideal having no frequency response variation error at the time of reception. Accordingly, the frequency response of
20 the transmission path can be accurately calculated by dividing the frequency response of the subcarriers in the first pilot symbol by those in the reference pilot symbol.

FIGS. 6a and 6b are schematic views respectively showing the first pilot symbol having subcarriers with a complex amplitude
25 of P1, and the reference pilot symbol having those with a complex

amplitude of P_r . The PS1 TPFR calculator 62 divides the complex amplitude P_1 as shown in FIG. 6a by the complex amplitude P_r as shown in FIG. 6b so as to calculate a frequency response of the transmission path P_a . An equation (1) therefor is as follows:

5
$$P_a(i) = P_1(i) \div P_r(i) \cdots (1)$$

where i is an arbitrary integer between 1 and N .

As described in the foregoing, when the pilot symbol is sequentially and plurally inserted, the frequency response of the transmission path is averaged for the pilot symbols. In this
10 manner, the frequency response of the transmission path for the pilot symbols can be estimated with higher accuracy.

With reference to FIG. 5 again, the PS2 TPFR calculator 63 divides the subcarriers in the second pilot symbol by those in the reference pilot symbol exemplarily stored in the memory in
15 the receiver, thereby estimating the frequency response of the transmission path for the second pilot symbol.

FIGS. 7a and 7b are schematic views respectively showing the second pilot symbol having the subcarriers with a complex amplitude of P_2 and the reference pilot symbol having those with
20 the complex amplitude of P_r . The PS2 TPFR calculator 63 divides the complex amplitude P_2 as shown in FIG. 7a by the complex amplitude P_r as shown in FIG. 7b so as to calculate a frequency response of the transmission path P_b . An equation (2) therefor is as follows:

25
$$P_b(i) = P_2(i) \div P_r(i) \cdots (2)$$

where i is an arbitrary integer between 1 and N .

As already described in the foregoing, when the second pilot symbol is sequentially and plurally inserted, the frequency response of the transmission path is averaged for the pilot symbols. In this manner, the frequency response of the transmission path for the second pilot symbols can be estimated with higher accuracy.

The compensation vector calculator 64 calculates a compensation vector V_k for each of the data symbols between the first and second pilot symbols. This is done by linear approximation between the first and second pilot symbol transmission path frequency responses P_a and P_b . The linear approximation is applicable herein since the pilot symbols are inserted with a shorter interval to make the transmission path linearly change in state, and the phase shift caused by frequency drift becomes linear with time. Therefore, by utilizing linear approximation, compensation can be linearly done with accuracy.

FIG. 8 is a graph having a longitudinal axis indicated the compensation vector V_k for each of the data symbols between the first and the second pilot symbols and a lateral axis the symbols by number, i.e., time, and the graph shows the relationship therebetween. As is known from FIG. 8, the compensation vector V_k for each of the data symbols can be calculated, through linear approximation, from a difference between the pilot symbols in frequency response of the transmission path.

It is now assumed that the number of data symbols between the first and second pilot symbols is M , and a certain data symbol therebetween is k , where k is an arbitrary integer between 1 and M . With such assumption and by using an equation (3) next below, the compensation vector V_k is calculated for each of the data symbols through linear approximation.

$$V_k(i) = Pa(i) + \frac{Pb(i) - Pa(i)}{M + 1} \times k \quad \dots (3)$$

where k is an arbitrary integer between 1 and M .

By using the compensation vectors calculated in such manner, the frequency response compensator 65 then compensates the frequency response variation of the subcarriers included in each of the data symbols between the first and second pilot symbols.

FIG. 9 is a schematic view showing how the frequency response variation of the k -th data symbol is compensated. With the compensation vectors, the frequency response variation of the subcarriers in each of the data symbols is compensated as follows with an equation (4).

$$C'_k(i) = C_k(i) / V_k(i) \quad \dots (4)$$

Such compensation is carried out with respect to the k data symbols between the first and second pilot symbols. Therefore, practically, these data symbols are once stored in a data symbol storage (not shown) provided in the receiver, for example. After the compensation vectors are calculated, the data symbols stored in the storage are read, and then the frequency response variation is compensated with respect to the data symbols.

Typically, such data symbol storage is provided preceding to or in the frequency response compensator 65. With respect to the data symbols stored therein, the compensation vector calculator 64 calculates the compensation vectors V_k respectively, and then the frequency response compensator 65 compensates the frequency response variation thereof.

In this manner, however, demodulation cannot be done for the period after the first pilot symbol is received and before the second pilot symbol is received, rendering the receiver of the first embodiment take a certain length of time for its processing. By taking this into consideration, the receiver of the first embodiment is more suitable for image transmission in which image is not required so soon to be retransmitted or under a broadcast transmission system.

In the above-described manner, the compensation vector can be calculated to compensate the frequency response variation resulted from the change in state of the transmission path for each of the subcarriers in the pilot symbol. Therefore, in the OFDM transmission scheme of the first embodiment, the compensation vector can be calculated with higher accuracy for every subcarrier compared with the conventional scheme for interposing the pilot carriers between the data carriers. Since the pilot carriers for insertion in the conventional scheme is quite fewer in number than the subcarriers, it is rather difficult to calculate the frequency response variation of the transmission

path, with accuracy, for the entire frequency band.

As such, the frequency response compensator 65 can free the received data from the frequency response variation of the transmission path. Especially when the transmission path
5 changes approximately linearly in state between the pilot symbols, the data symbols can be correctly demodulated even in the multipath fading environment or the high-level-noise environment. This is enabled by compensating, through linear approximation, the frequency response of the data symbols between the pilot
10 symbols. Further, the phase shift caused by the frequency drift is linear with time, allowing linear compensation with accuracy.

In a case where the transmission path does not change in state that much, the frequency response variation of the transmission path for the data symbols may be compensated by using
15 only one pilot symbol preceding thereto. Accordingly, the frequency response variation of the transmission path for the data symbols can be compensated without receiving another pilot symbol subsequent thereto.

(Second Embodiment)

20 A transmission scheme according to a second embodiment of the present invention is quite similar to the one described in the first embodiment. Further, a transmitter of the second embodiment is structurally identical to the one in the first embodiment, and is not described twice. As to a receiver of the
25 second embodiment, however, is partially different in structure

from the one in the first embodiment, and thus description is made focusing on the difference.

FIG. 10 is a schematic view showing the structure of the receiver of the second embodiment. The receiver is provided with the Fourier transformer 5, a phase compensator 26 for compensating a phase of a signal provided by the Fourier transformer 5, and the demodulator 7 for demodulating a signal outputted from the phase compensator 26. As such, the receiver of the second embodiment includes the phase compensator 26 as an alternative to the TPFR compensator 6 in the receiver in FIG. 4.

The phase compensator 26 frees data provided by the Fourier transformer 5 from frequency drift and residual phase error. The phase compensator 26 is later structurally described in detail. The data freed from error is demodulated by the demodulator 7.

FIG. 11 is a schematic view showing the detailed structure of the phase compensator 26 in the receiver of the second embodiment. The phase compensator 26 includes: a PS detector 261 for detecting a pilot symbol from a signal provided by the Fourier transformer 5; a PS1 phase difference calculator 262 for calculating a difference in phase between the first pilot symbol provided by the PS detector 261 and a predetermined reference pilot symbol; a PS1-PS2 phase difference calculator 263 for calculating a difference in phase between the pilot symbols provided by the PS detector 261; a phase compensation value calculator 264 for calculating a phase compensation value after

receiving outputs from the PS1 phase difference calculator 262 and the PS1-PS2 phase difference calculator 263; and a phase rotator 265 for rotating a phase of a signal provided by the PS detector 261 on the basis of an output from the phase compensation value calculator 264. The above description for "PS", "PS1", "PS2" is herein also applicable to the above components.

The PS detector 261 detects, in a similar manner to the PS detector 61 in FIG. 5, a pilot symbol from the Fourier-transformed frequency-domain data. The PS1 phase difference calculator 262 calculates a difference in phase between the subcarriers in the first pilot symbol and those of the reference pilot symbol stored in memory (not shown) in the receiver.

The reference pilot symbol stored in the memory is also an ideal pilot symbol as is the one in the receiver of the first embodiment. Accordingly, by calculating the difference in phase between the subcarriers in the first pilot symbol and those in the reference pilot symbol, a phase error caused by transmission can be obtained.

FIGS. 12a and 12b are schematic views respectively showing the first pilot symbol having the subcarriers with a phase of ϕ_1 and the reference pilot symbol having those with a phase of ϕ_r . The PS1 phase difference calculator 262 calculates a difference ϕ_{ps} between the phase ϕ_1 as shown in FIG. 12a and the phase ϕ_r as shown in FIG. 12b so as to calculate the phase error of the first pilot symbol. An equation (5) therefor is as follows:

$$\phi_{ps}(i) = \phi_l(i) - \phi_r(i) \quad \dots (5)$$

where i is an arbitrary integer between 1 and N .

The PS1 phase difference calculator 262 averages the phase difference for the number of subcarriers. Assuming that the averaged value is ϕ_p , an equation (6) therefor is as follows:

$$\phi_p = \frac{1}{N} \sum_{i=1}^N \phi_{ps}(i) \quad \dots (6)$$

The received signal distorts in the transmission path and by noise. Therefore, in order to obtain ϕ_p , each carrier in the received pilot symbol is weighed according to its amplitude before calculating the average value. As thereto, it is described how next below.

Presumably, a complex signal of the i -th subcarrier in the received first pilot symbol is $A1(i)$, that of the i -th subcarrier in the received second pilot symbol is $A2(i)$, and an amplitude of the i -th subcarrier in the reference pilot symbol is $R(i)$. With such assumption, the average value ϕ_p can be calculated by the following equation (7).

$$\begin{aligned} \phi_p &= -\text{angle} \left[\sum_{i=1}^N \left(\frac{R(i)}{A1(i)} |A1(i)|^2 \right) \right] \\ &= -\text{angle} \left[\sum_{i=1}^N (R(i) \times A1(i)^*) \right] \quad \dots (7) \end{aligned}$$

where an asterisk $*$ indicates complex conjugate, and a term "angle" a phase angle of complex number.

With such equation of calculating the average value, each component is weighed by the power level of the complex signal $A1(i)$.

Consequently, any carrier larger in amplitude may contribute more with respect to the average value, and vice versa. In such manner, even if the received signal distorts in the transmission path and by noise, the average value can be calculated with higher
5 accuracy.

The PS1-PS2 phase difference calculator 263 then calculates a difference in phase between the subcarriers in the first pilot symbol and those in the second pilot symbol.

FIGS. 13a and 13b are schematic diagrams respectively
10 showing the first pilot symbol having the subcarriers with the phase of $\phi 1$ and the second pilot symbol having the subcarriers with a phase of $\phi 2$. The PS1-PS2 phase difference calculator 263 calculates a phase difference ϕ between the phase $\phi 1$ as shown in FIG. 13a and the phase $\phi 2$ as shown in FIG. 13b. An equation
15 (8) therefor is as follows:

$$\phi(i) = \phi 1(i) - \phi 2(i) \quad \dots (8)$$

where i is an arbitrary integer between 1 and N .

The PS1-PS2 phase difference calculator 263 averages the phase difference for the number of subcarriers. Assuming that
20 the averaged value is ϕa , an equation (9) therefor is as follows:

$$\phi a = \frac{1}{N} \sum_{i=1}^N \phi(i) \quad \dots (9)$$

In the above-described manner, the phase error can be correctly calculated for entire frequency covering every subcarriers by averaging the phase error for the number of

subcarriers in the pilot symbol. Therefore, in the OFDM transmission scheme of the second embodiment, the phase error can be calculated with higher accuracy compared with the conventional scheme for interposing the pilot carriers between the data carriers. Since the pilot carriers for insertion in the conventional scheme is quite fewer in number than the subcarriers, it is rather difficult for the conventional scheme to correctly calculate the phase error for the entire frequency band.

In order to calculate such average value more accurately, in a similar manner to the above, each carrier in the received pilot symbol is weighed according to its amplitude before calculating the average value. As thereto, assuming also that the average value is ϕa , an equation (10) therefor is as follows:

$$\begin{aligned}\phi a &= \text{angle} \left[\sum_{i=1}^N \left(\frac{A2(i)}{A1(i)} |A1(i)|^2 \right) \right] \\ &= \text{angle} \left[\sum_{i=1}^N (A2(i) \times A1(i)^*) \right] \quad \dots (10)\end{aligned}$$

With such equation of calculating the average value, each component is weighed by the power level of the complex signal $A1(i)$. Consequently, any carrier larger in amplitude may contribute more with respect to the average value, and vice versa. In such manner, even if the received signal distorts in the transmission path and by noise, the average value can be calculated with higher accuracy.

In such manner, however, unlike the receiver of the first embodiment, the compensation value cannot be calculated for each

of the subcarriers. From a different point of view, on the other hand, accuracy of compensation may be degraded by calculating the compensation value each for the subcarriers in such case that some of the subcarriers in the pilot symbol is suppressed or vanished.

5 By taking this into consideration, the receiver of the second embodiment works effective especially for frequency drift and phase shift distorting every carrier to almost the same extent. More specifically, the receiver of the second embodiment is suitable for communications carried out in a static transmission
10 path with a smaller distortion. Conversely, the receiver of the first embodiment is suitable for mobile communications where distortion level of the transmission path varies or out-of-synchronization is observed with time.

The phase compensation value calculator 264 calculates a
15 phase compensation value ϕ_d for each of the data symbols between the first and second pilot symbols. This is done through linear approximation by the phase difference ϕ_a between the pilot symbols. The linear approximation is applicable herein since the phase shift caused by the frequency drift becomes linear with time.
20 Therefore, by utilizing linear approximation, compensation can be linearly done with accuracy.

FIG. 14 is a graph having a longitudinal axis indicated the phase compensation value ϕ_d for each of the data symbols between the first and the second pilot symbols and a lateral axis the
25 symbols by number, i.e., time, and the graph shows the

relationship therebetween. As is known from FIG. 14, the phase compensation value ϕd for each of the data symbols can be calculated, through linear approximation, from the phase compensation value ϕd between the pilot symbols.

5 It is now assumed that the number of data symbols between the first and second pilot symbols is M , and a certain data symbol therebetween is k , where k is an arbitrary integer between 1 and M . With such assumption and by using an equation (11) next below, the phase compensation value ϕd is calculated for each of the
10 data symbols through linear approximation.

$$\phi d(k) = \phi p + \frac{\phi a}{M+1} \times k \quad \dots (11)$$

With the phase compensation values calculated in such manner, the phase rotator 265 then compensates the phase of the subcarriers in each of the data symbols between the first and second pilot symbols. FIG. 15 is a schematic view showing how
15 the k -th data symbol is compensated in phase. The subcarriers in each of the data symbols are compensated in phase by utilizing the calculated phase compensation value. An equation (12) therefor is as follows:

$$C'k(i) = Ck(i) \times \exp(j \cdot \phi d(k)) \quad \dots (12)$$

20 where i and k are respectively an arbitrary integer between 1 and N .

Such phase compensation is done with respect to the M data symbols between the first and second pilot symbols. Therefore,

as in the receiver of the first embodiment, such data symbols are practically once stored in a data symbol storage (not shown). After the phase compensation values are calculated, the data symbols stored in the data symbol storage are read, and then phase
5 compensation is carried out with respect thereto. By taking this into consideration, like the receiver of the first embodiment, the receiver of the second embodiment is more suitable for image transmission in which image is not required so soon to be retransmitted or under a broadcast transmission system.

10 As such, the phase compensator 26 frees the received data from frequency drift and residual phase error. The data symbols can be correctly demodulated even in the multipath fading environment or the high-level-noise environment by compensating, through linear approximation, the phase error of the data symbols
15 between the pilot symbols. Further, the phase shift caused by the frequency drift is linear with time, allowing linear compensation with accuracy. Therefore, the receiver and reception method of the second embodiment are effective especially for linear phase error such as frequency drift.

20 As shown in the above equation (12), in the receiver of the second embodiment, every subcarrier included in one data symbol is subjected to phase compensation with a single phase compensation value. Therefore, compared with the TPFRC compensator 6 in the receiver of the first embodiment in which
25 the frequency response variation is compensated by using

compensation values calculated for each subcarrier, the phase compensator 26 of this receiver is simplified in structure.

To be more specific, the frequency response compensator 65 in the TPFR compensator 6 is internally provided with memory for storing the compensation values for each of the subcarriers, and performing control and calculation with respect to each of the subcarriers by using the compensation values therefor. On the other hand, the phase rotator 265 in the phase compensator 26 is provided with memory for storing only one compensating value, and performing control and calculation therewith, rendering the structure thereof more simplified.

While the invention has been described in detail, the foregoing description is in all aspects illustrative and not restrictive. It is understood that numerous other modifications and variations can be devised without departing from the scope of the invention.